Near Wellbore Physics

Non-isothermal flow into a wellbore

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Schlumberger

Excerpt from the Proceedings of the 2011 COMSOL Conference in Boston

Near Wellbore Physics in Oilfield Exploration

- Industry background
- Simplistic approach to determining flow profiles
- Actual data
- Role of multi-physics modeling
- Some initial results and future research directions
- Conclusion

Industry Background – Exploration and Production

- Wellbores are drilled into the ground to extract hydrocarbon (gas/oil) from within the pores and fractures of a reservoir, usually with water in the same pores
- The zones will be of different permeabilities and pressures, and the pressures will drop over time as the reservoir depletes
- Only about 20-30% of the oil is ultimately recovered, even with hundreds of wells drilled into the same reservoir
- Finding new reserves is important, but improving production ratio even more so.

Industry Background – Exploration and Production

- Production improvement by increasing permeability
  - Hydro-Fracking, Acid Stimulation,etc
- Production improvement by increasing pressure
  - Drill nearby well and inject water, gas, or both
- Production improvement by increasing viscosity of oil
  - Drill very-nearby well and pump steam to heat the oil
- Difficult to improve production without knowing what fluids are being produced, and from where along the wellbore

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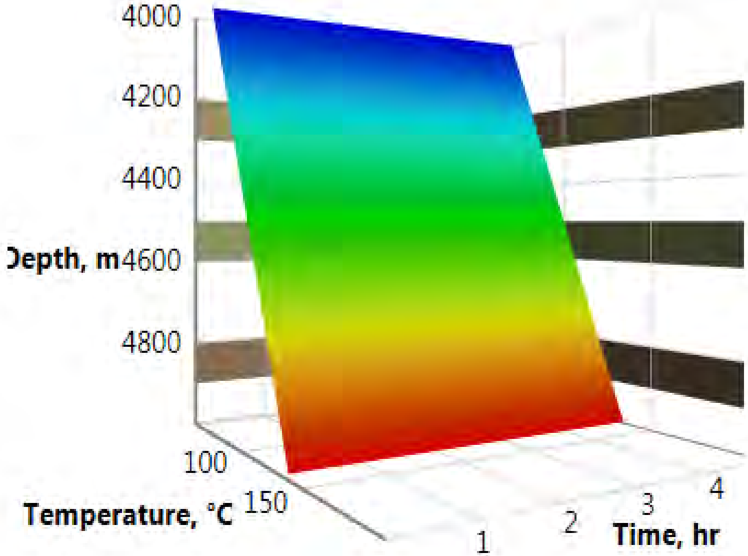
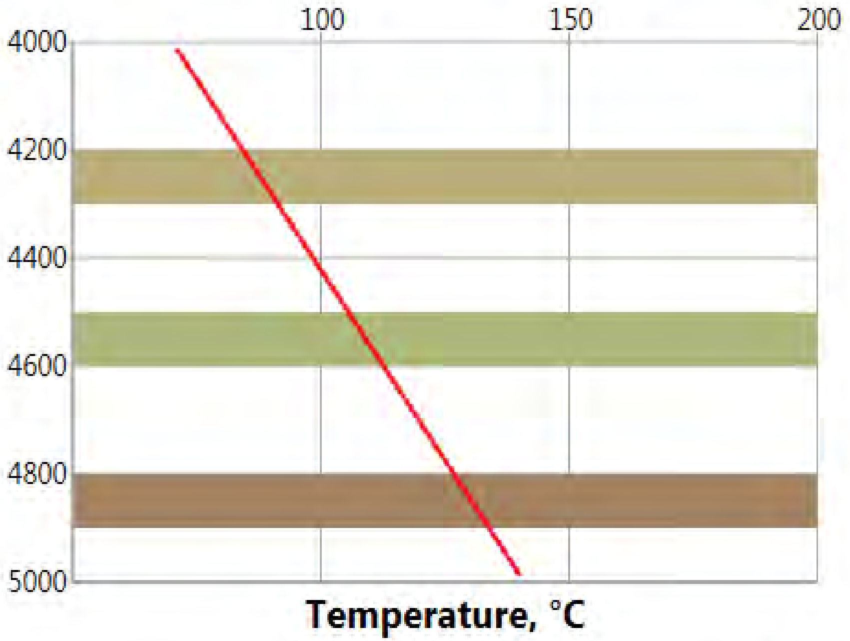
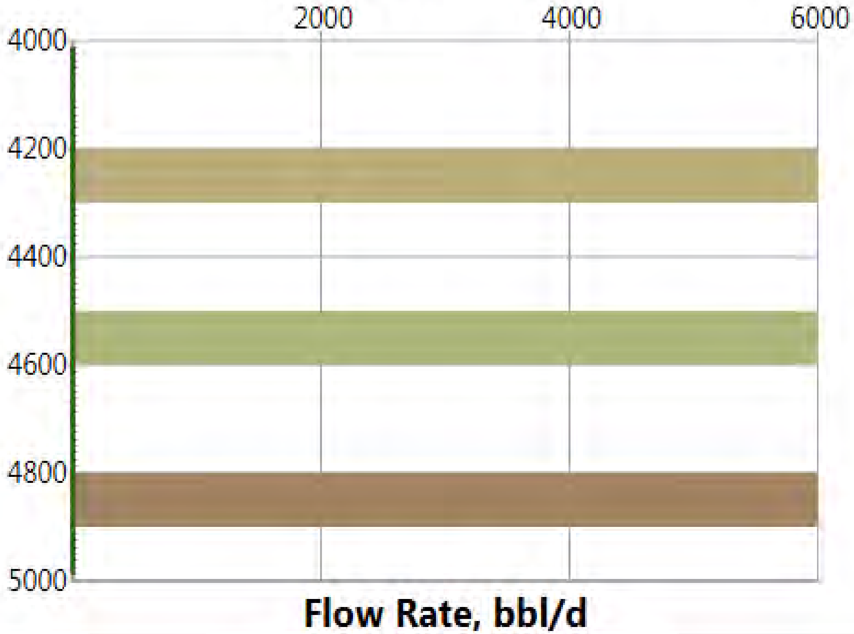
Role of Temperature Profiling







	Water Cut	Gas/Oil Ratio	Flow Rate
Zone 1			
Zone 2			
Zone 3			

Therma

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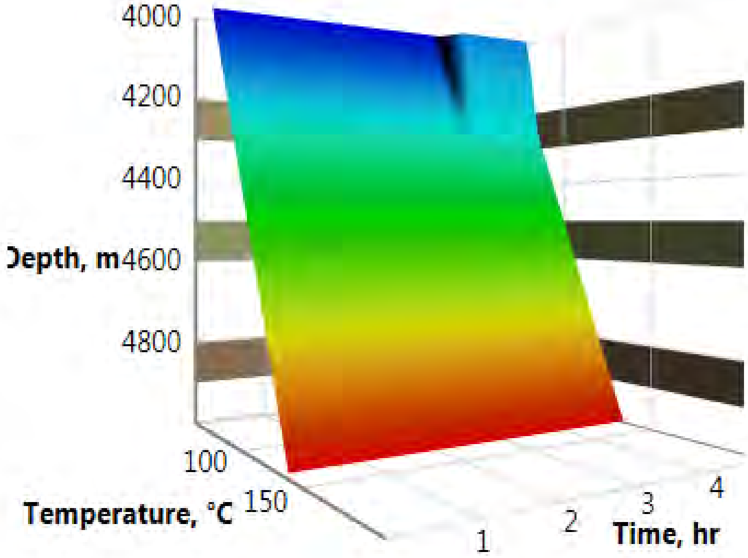

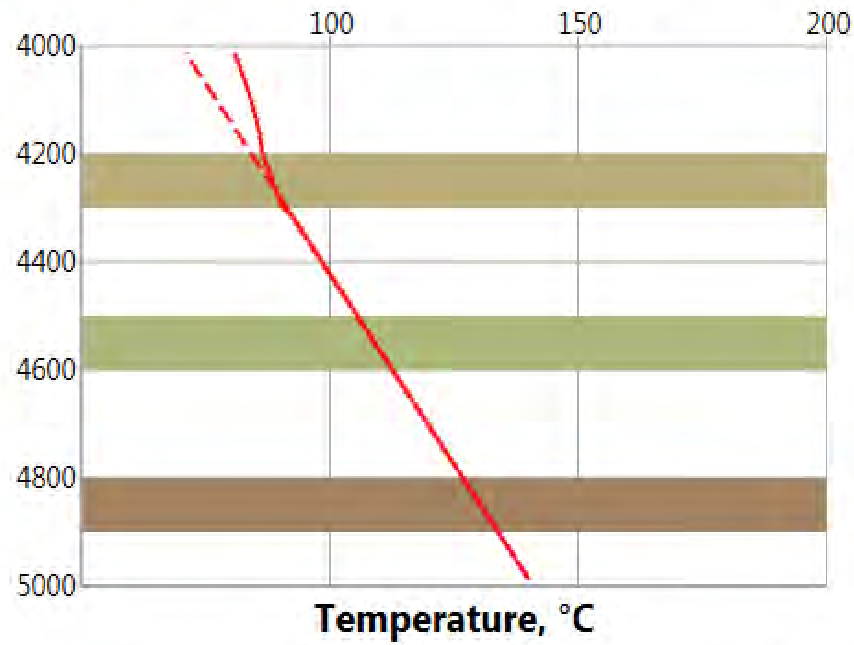

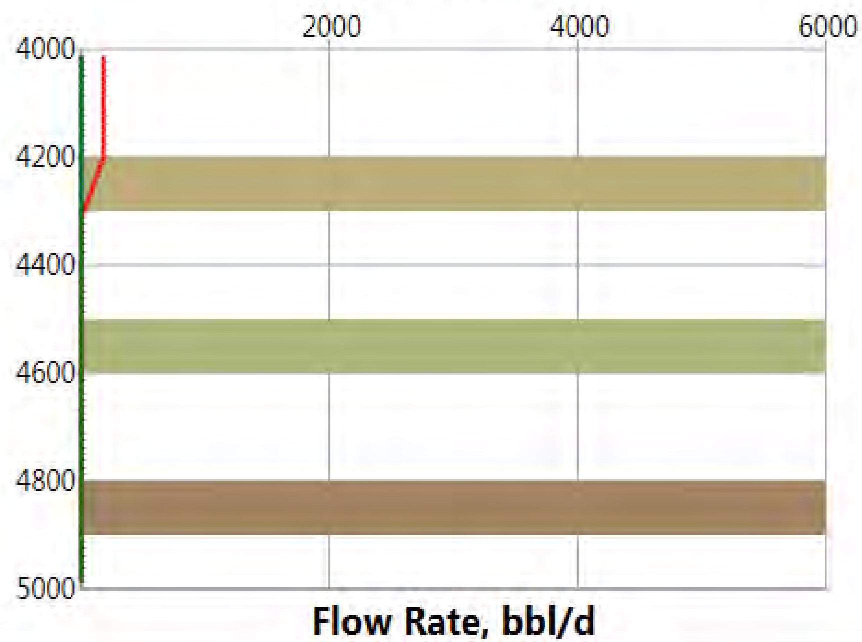

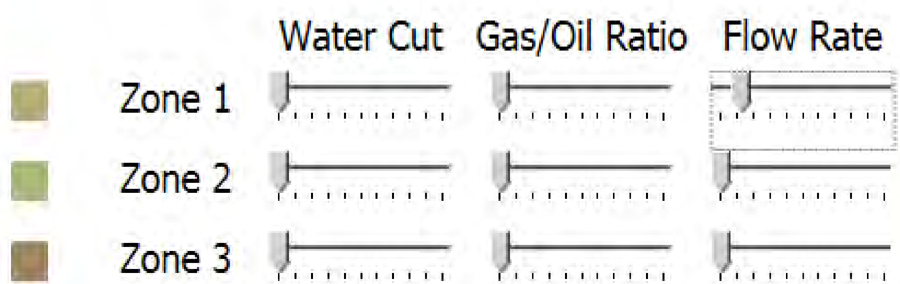

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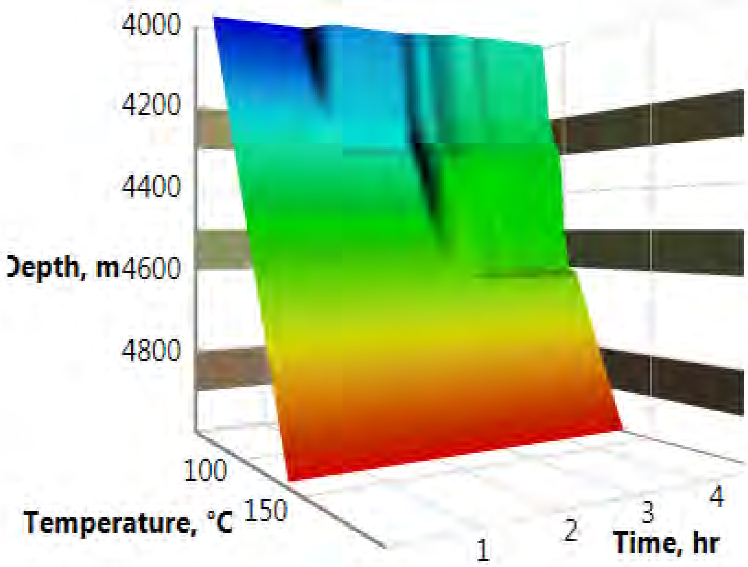

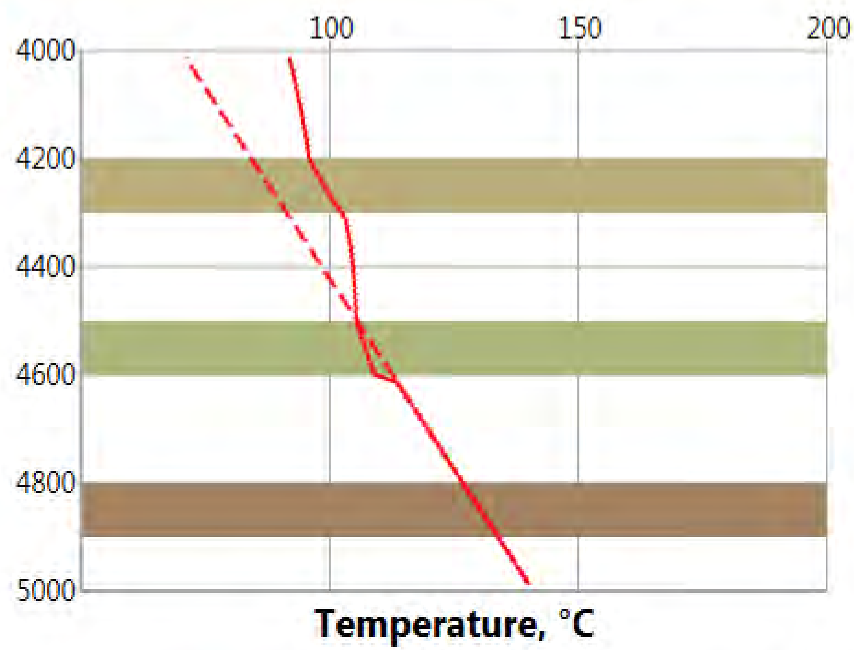

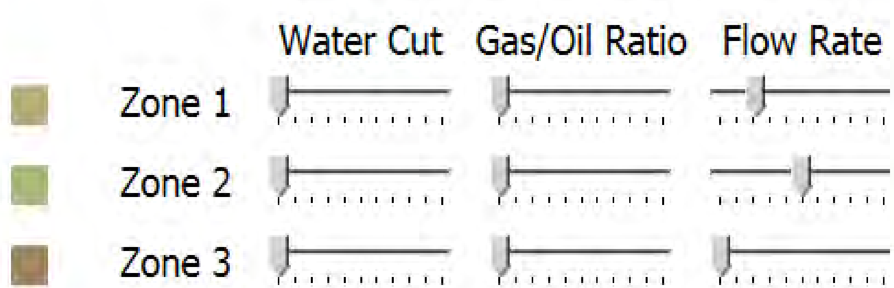

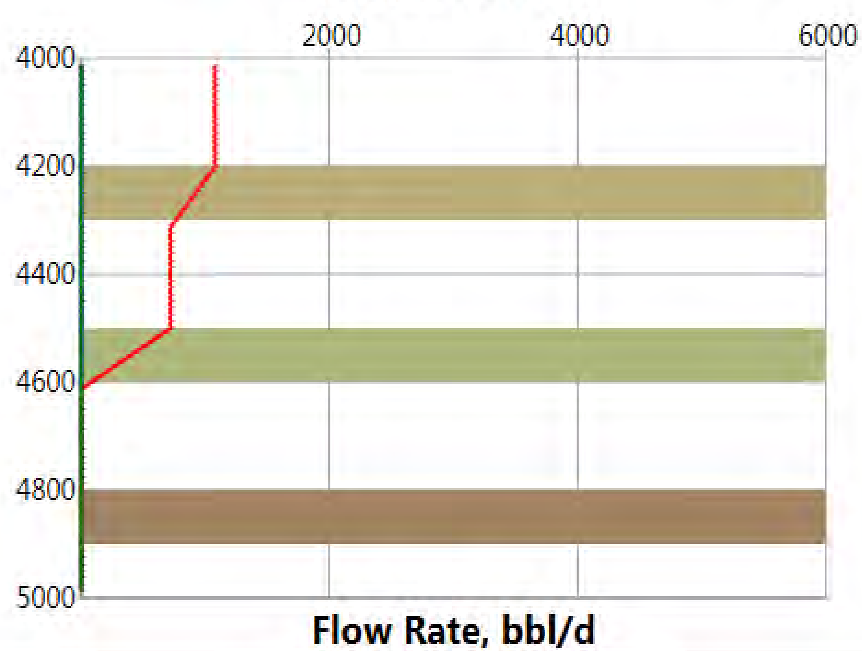

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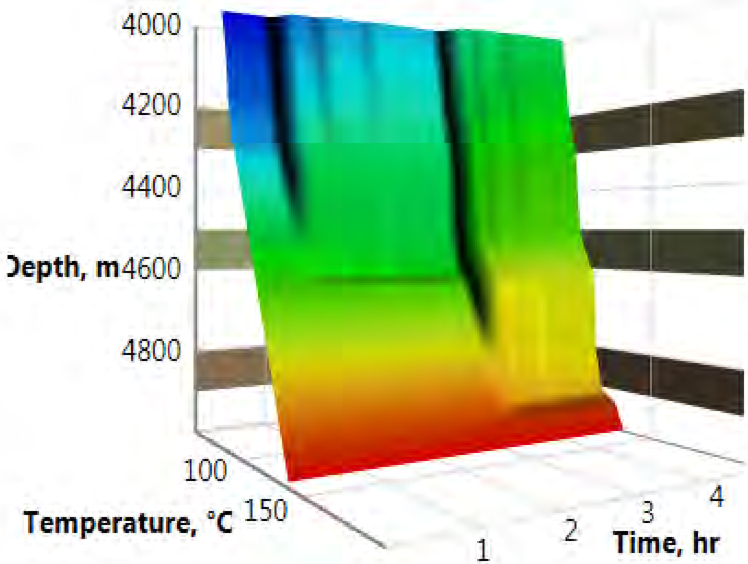

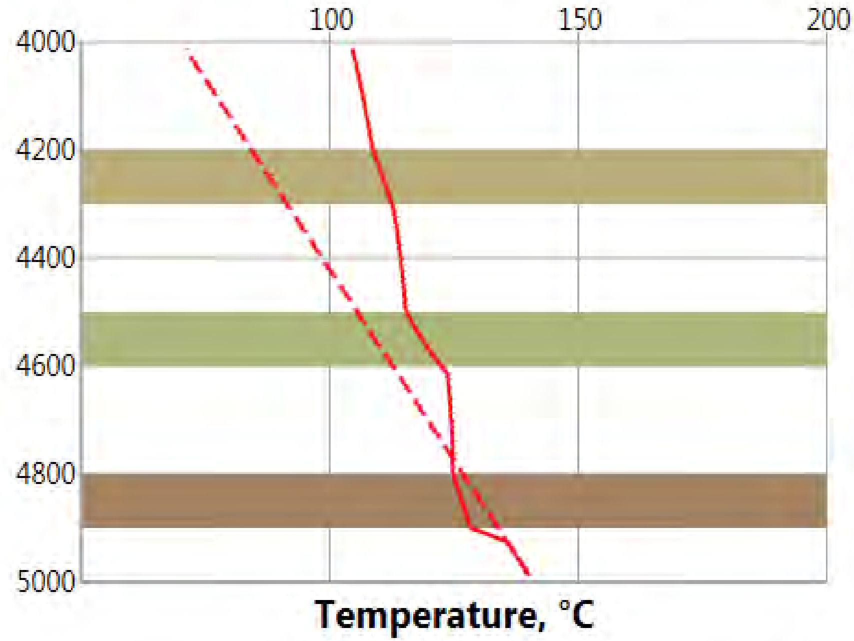

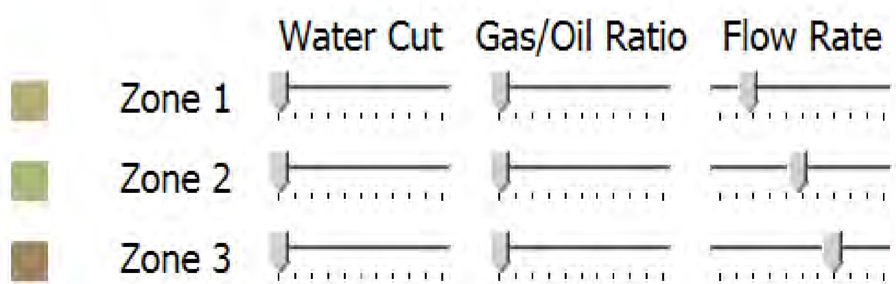

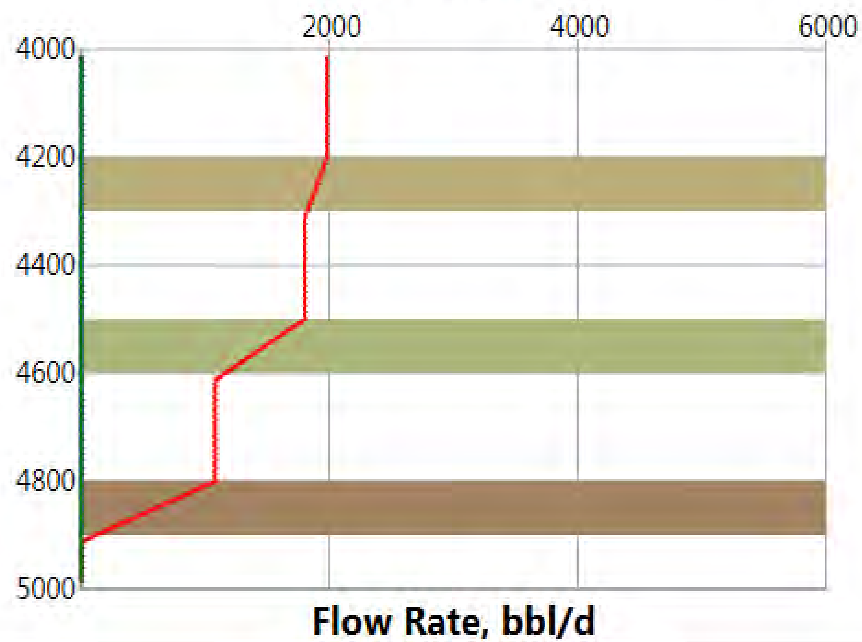

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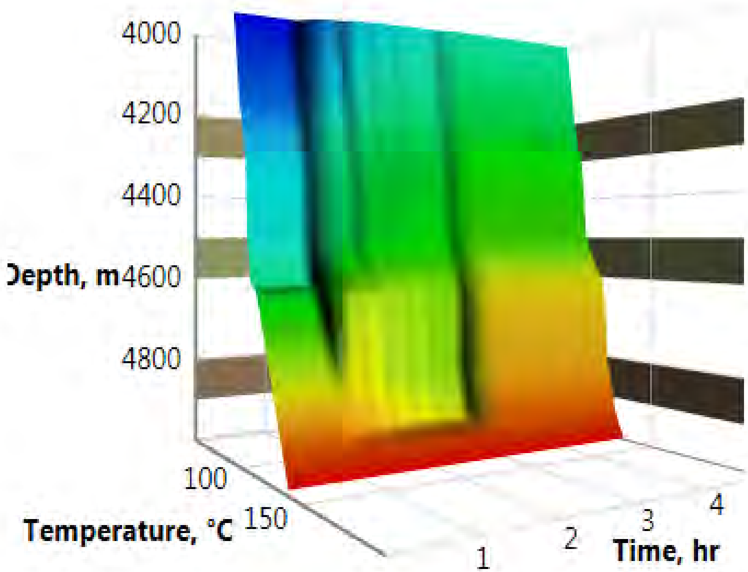
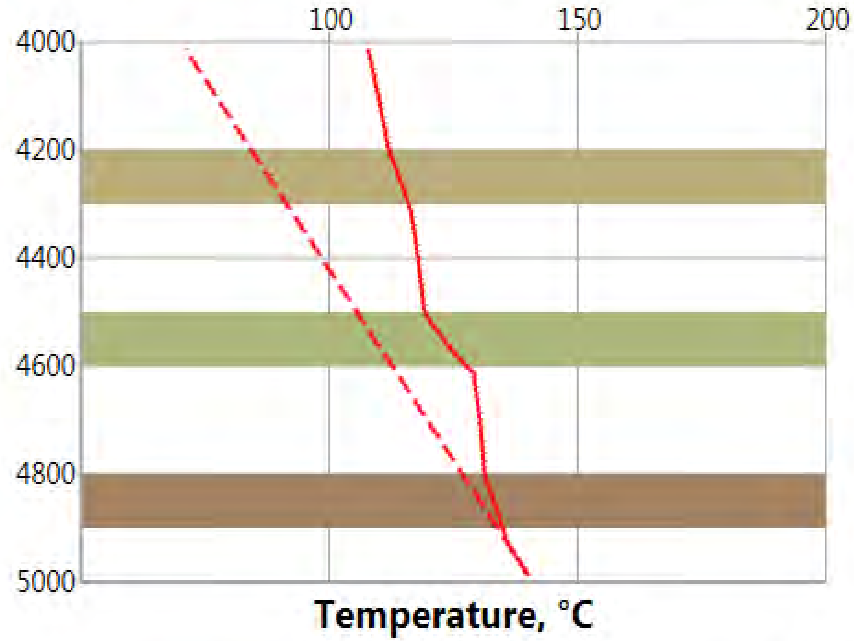
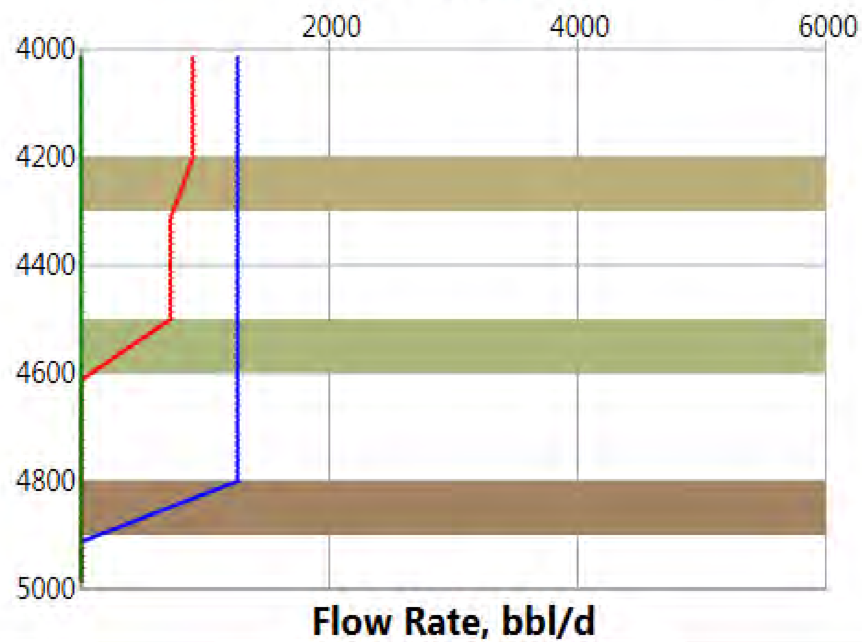
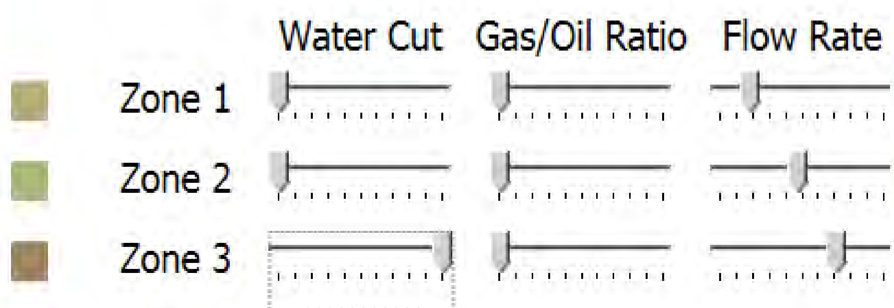








Role of Temperature Profiling

- Measure/Estimate/Model incoming fluid temperature
- Measure fluid temperature along wellbore
  - ⟹ Flow profile – identify major flowing zones
  - ⟹ Evaluate effectiveness of stimulation/injection/etc

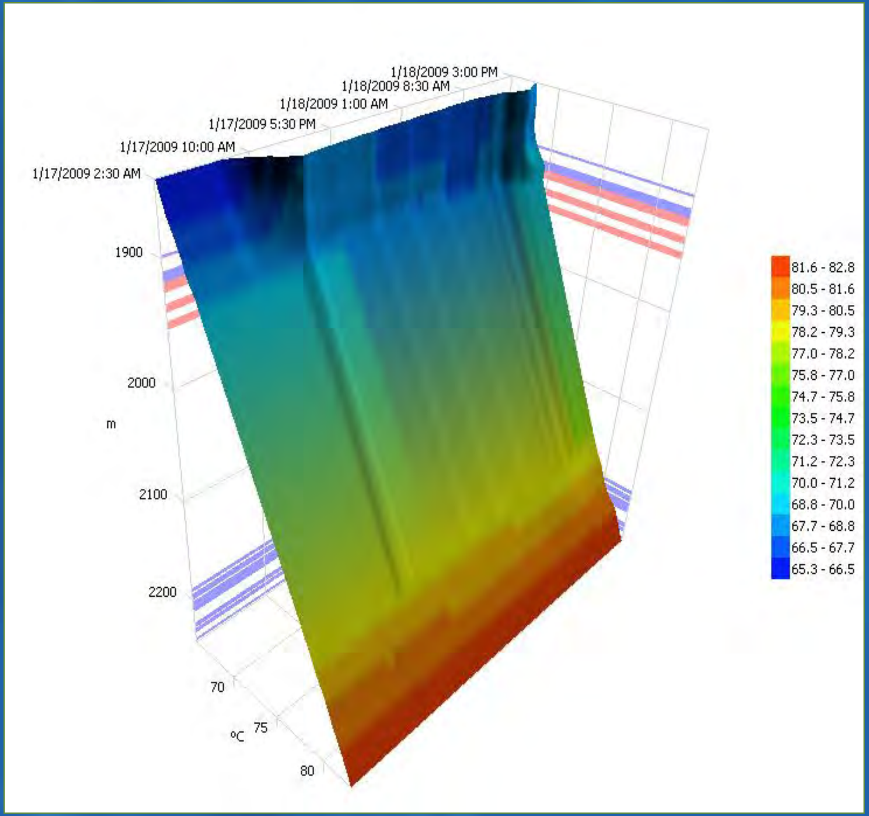
- How to measure temperature?

DTS: Fundamental Single Ended Principle

Schlumberger

Subsea Data from Array of Sensors

Clean-up of gas well

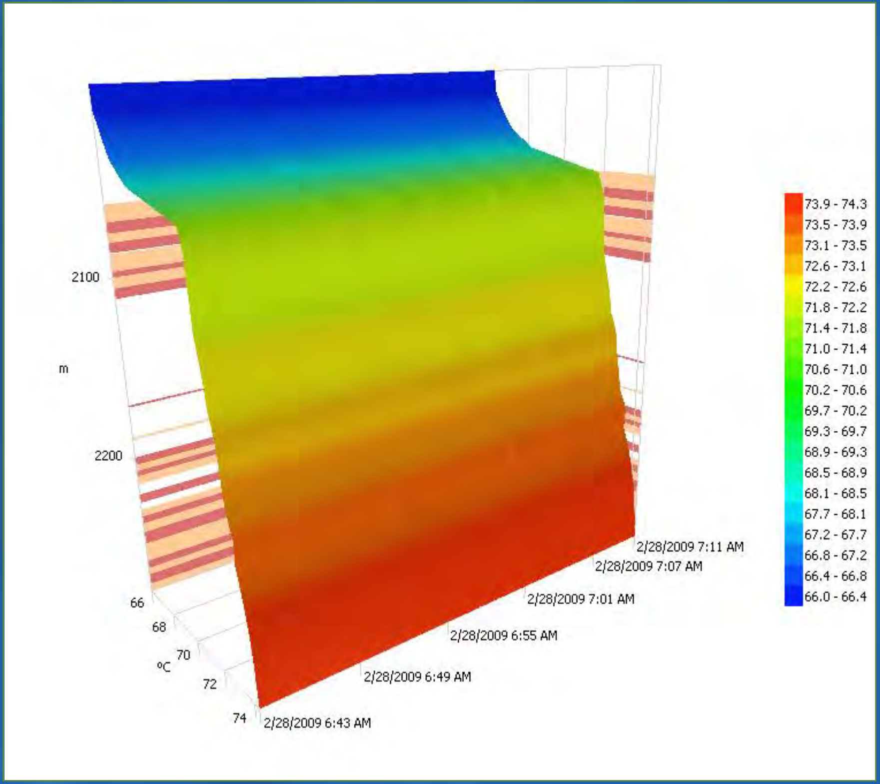


Top zone cleaned successfully
Bottom zone barely starting
Bottom zone still had brine – had absorbed lot of the fluid during stimulation

When this well is brought online into production facilities, need to plan for some initial some fluid production before the dry gas

Subsea Data from Array of Sensors

Cross-Flow Before Production



Fluid migrating from lower zone to upper.

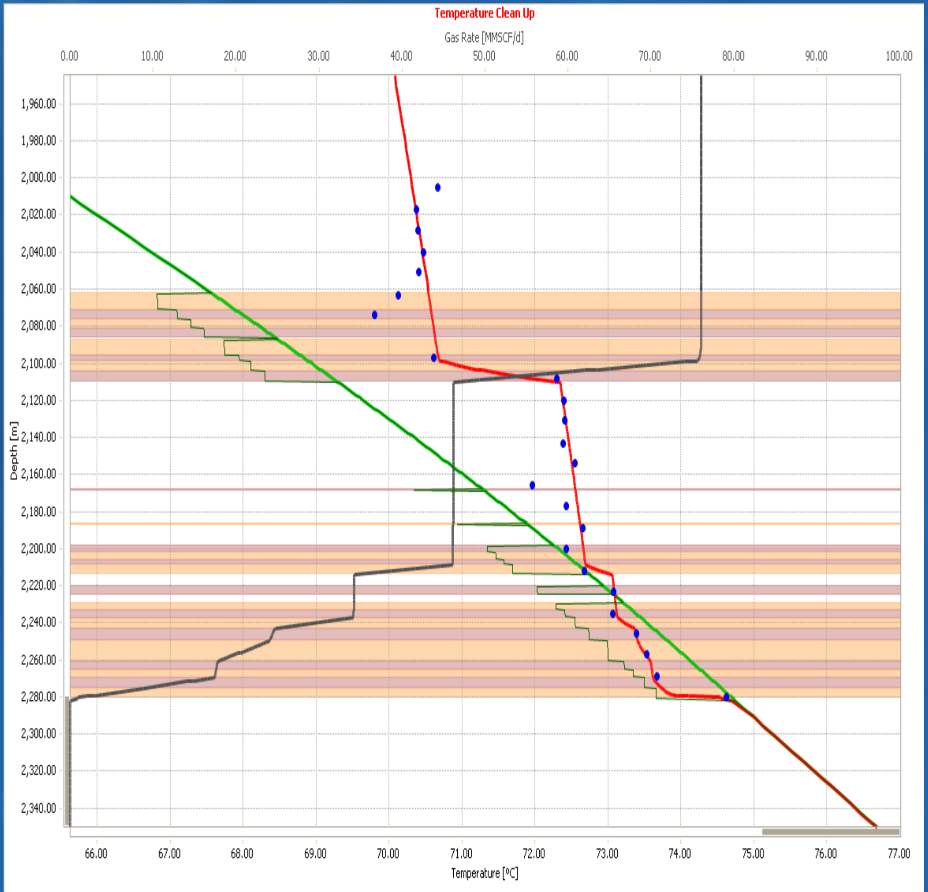
Well had been completed many months earlier, yet cross-flow still stable.

Indicative of relatively large reservoirs and anomalous pressured zones.

Led operator to re-evaluate drill-stem test data.

Subsea Data from Array of Sensors

Not all wells so simple to interpret

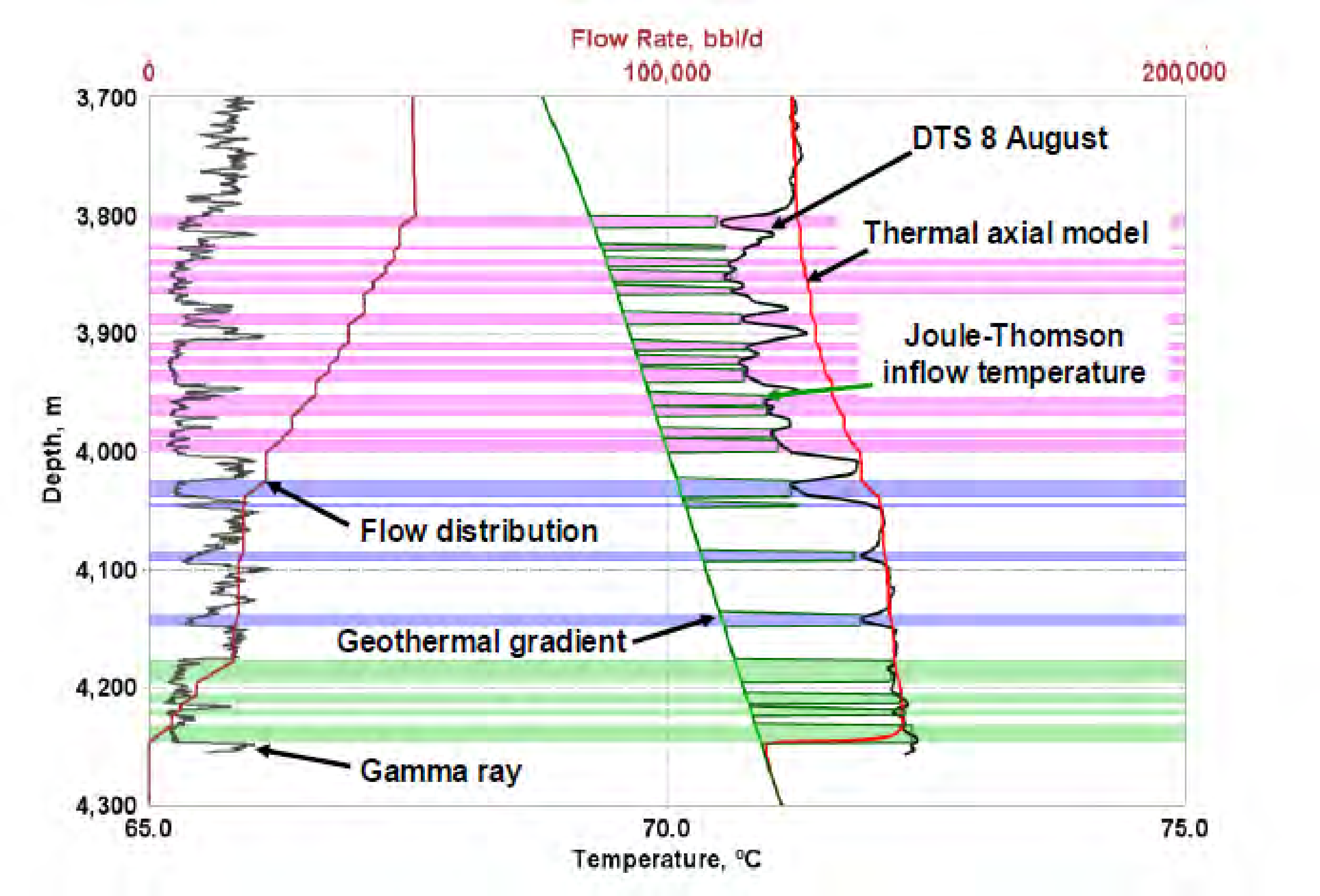


Fewer than 30 sensors across sandface

Some sensors directly in front of gas impingement reading much colder than the average wellbore temperature

Similar phenomenon have been since been seen in DTS in fractured shale gas wells.

Azeri Sandface Data



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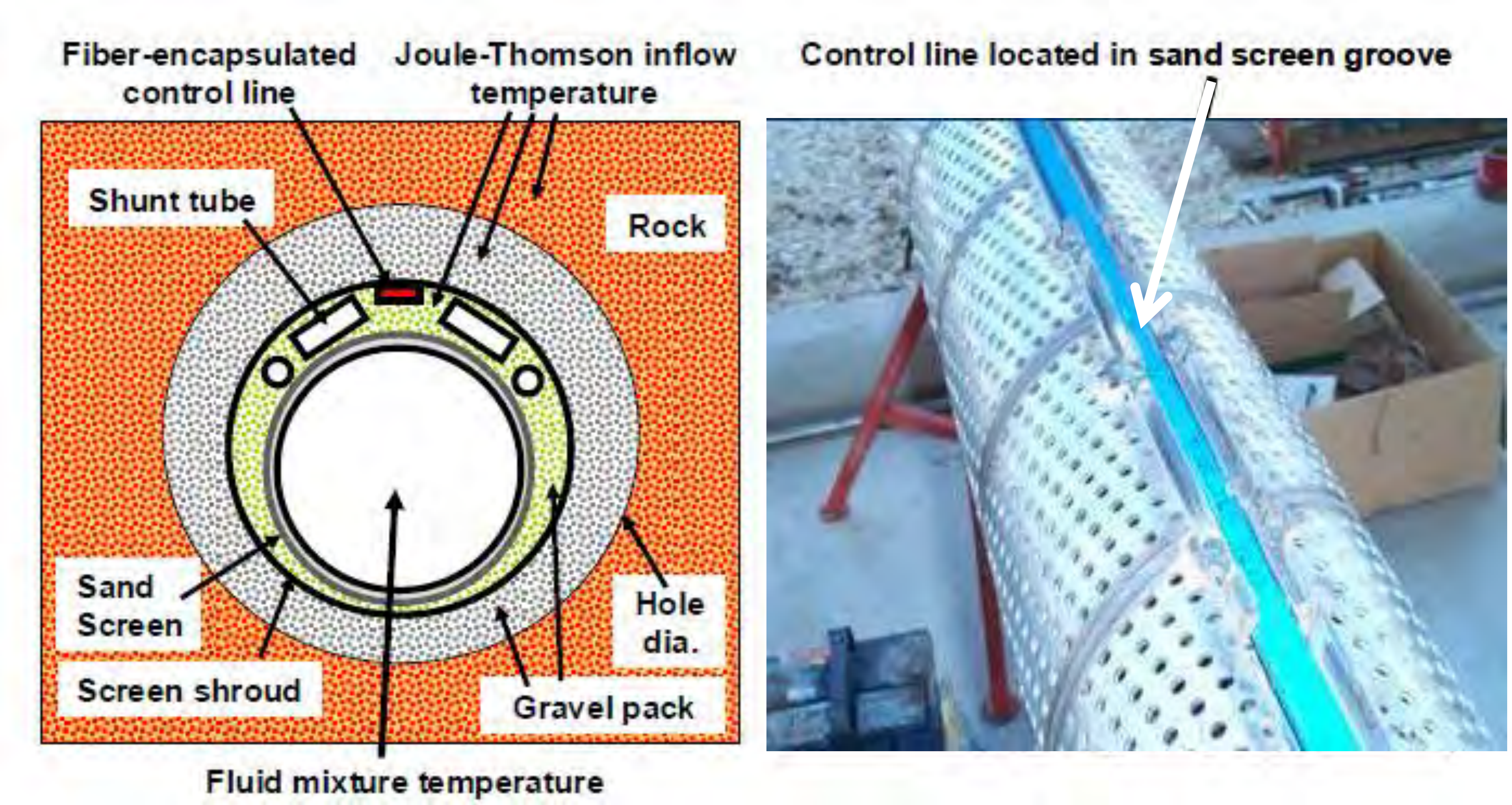

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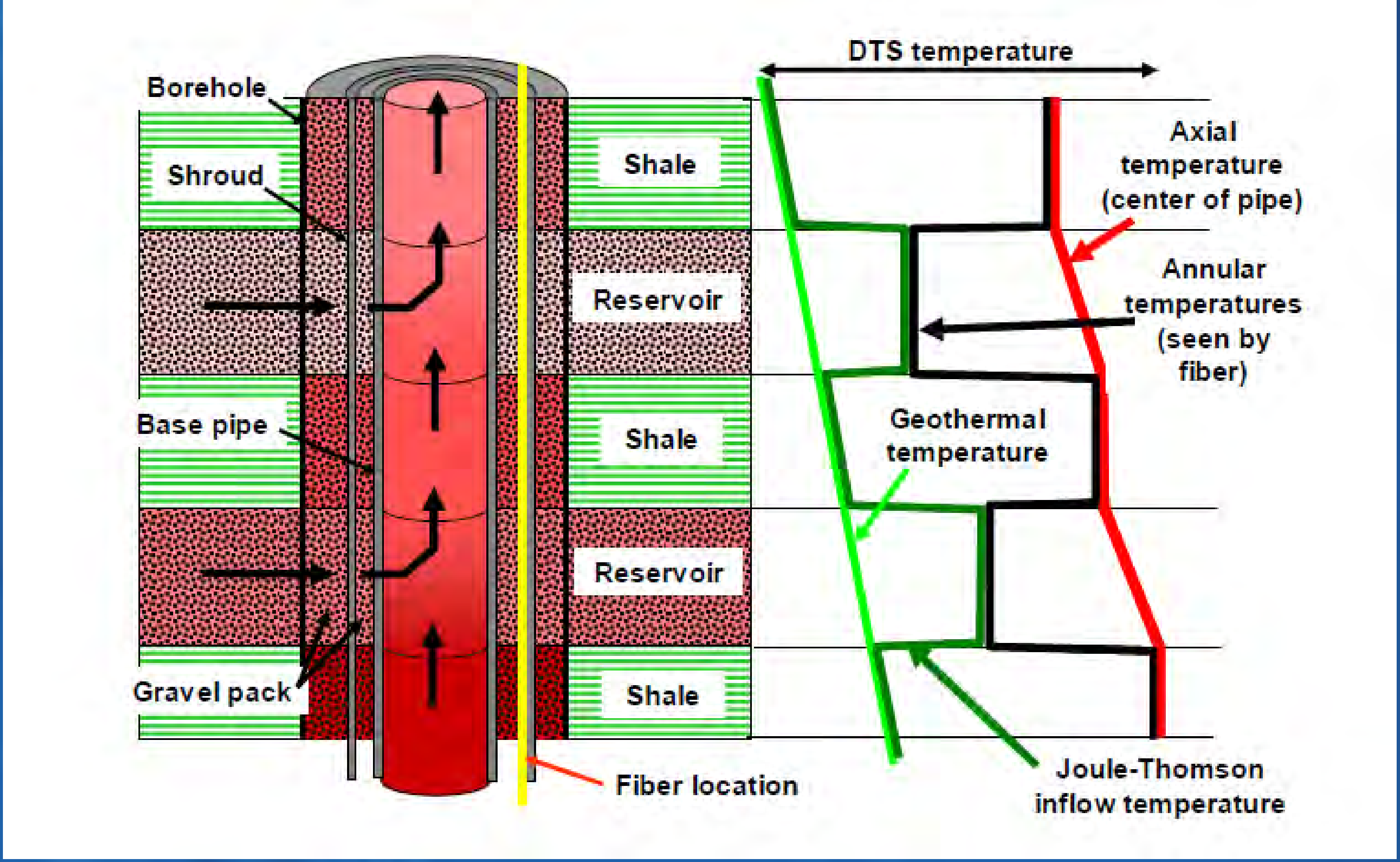
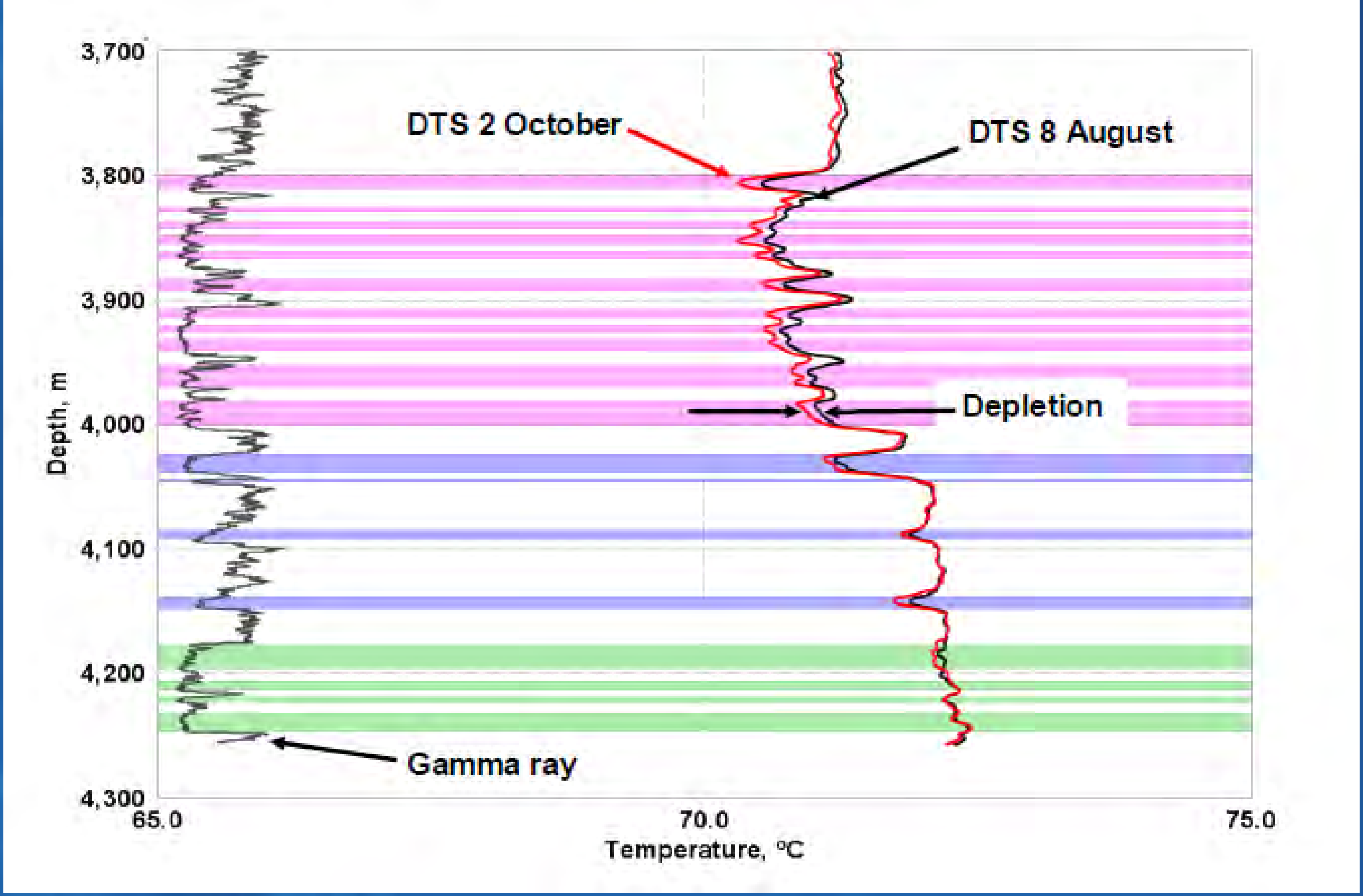


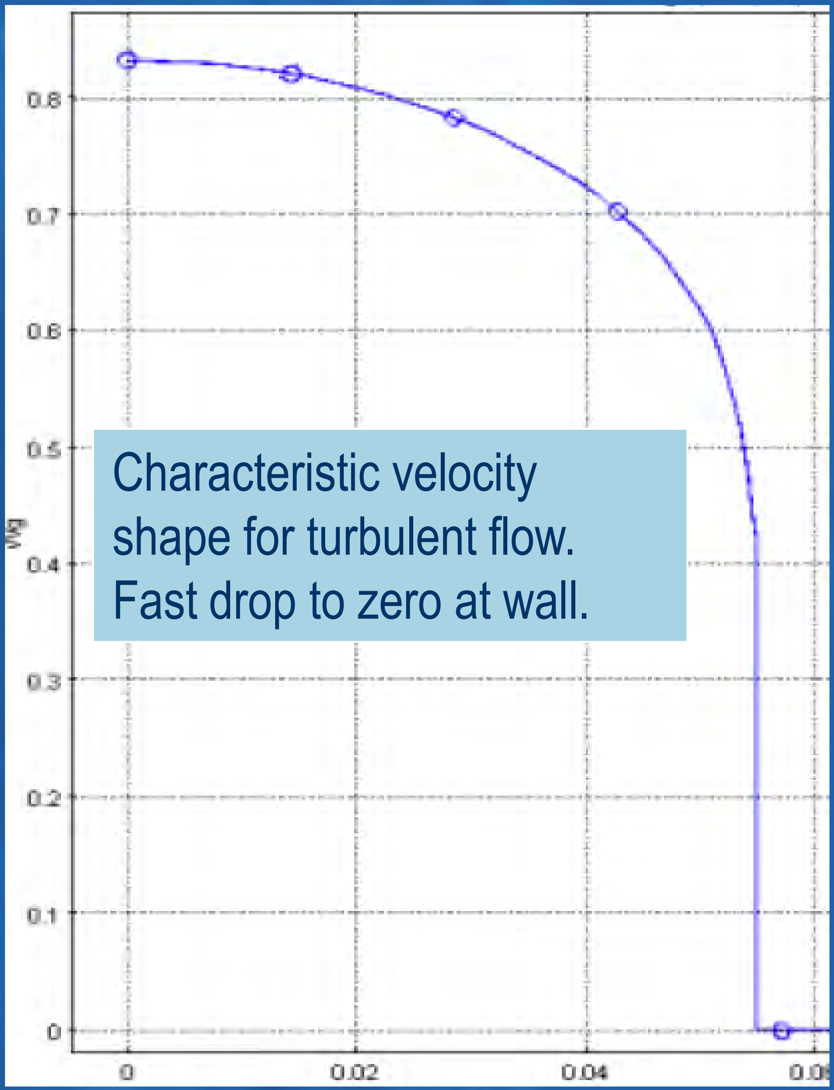
Azeri Sandface Data – Pressure Depletion

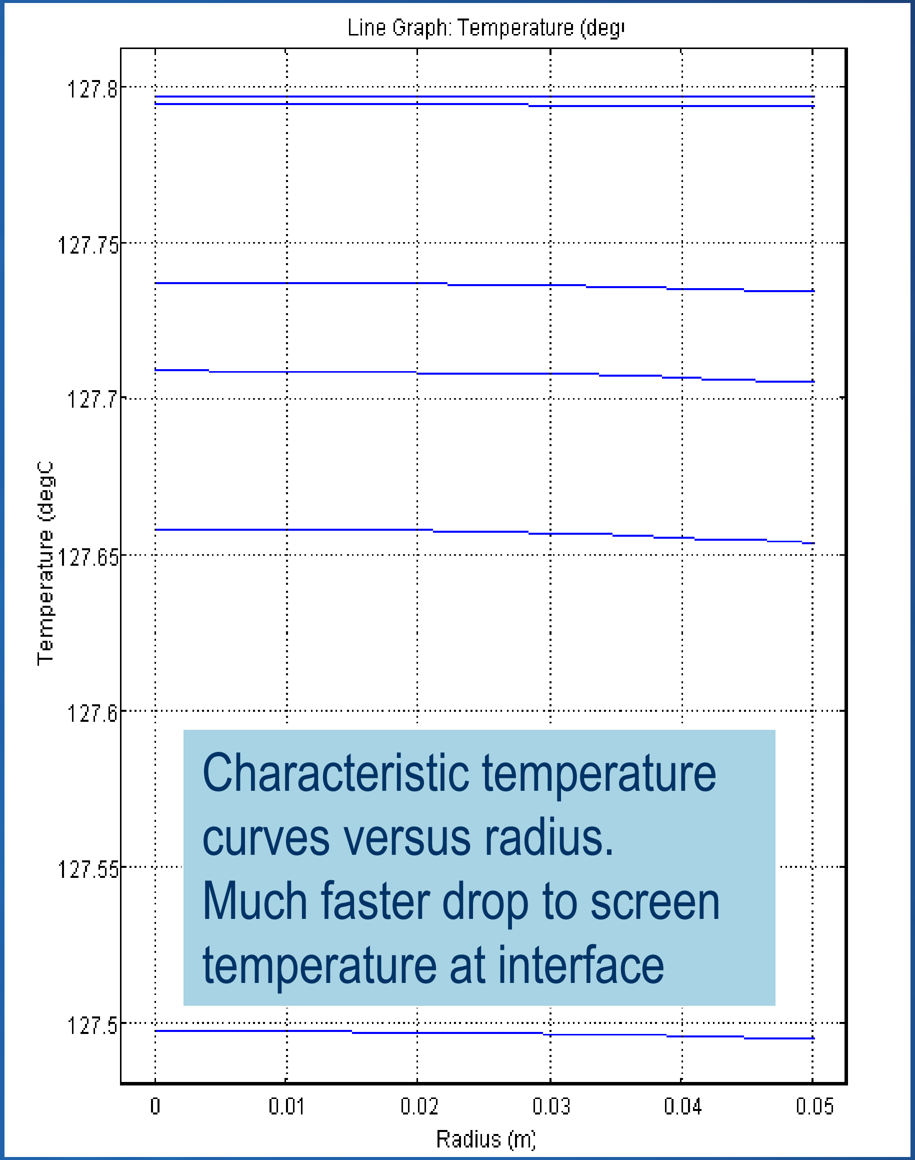


What temperature does DTS measure?

- Temperature on outside of screens not same as average wellbore temperature
- Temperature on screens depends on incoming flow rate – advection versus conduction
- Temperature on the inside of a screen not the same as temperature on the outside of screen
- Temperature on the inside of a screen not the same as the average wellbore temperature

Velocity vs Temperature Profile in Wellbore





Go to equations – Wellbore

$$\bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}_r\frac{\partial \bar{u}}{\partial r} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x} + \frac{1}{r}\frac{\partial}{\partial r}\left((\upsilon + \varepsilon_M)r\frac{\partial \bar{u}}{\partial r}\right)$$

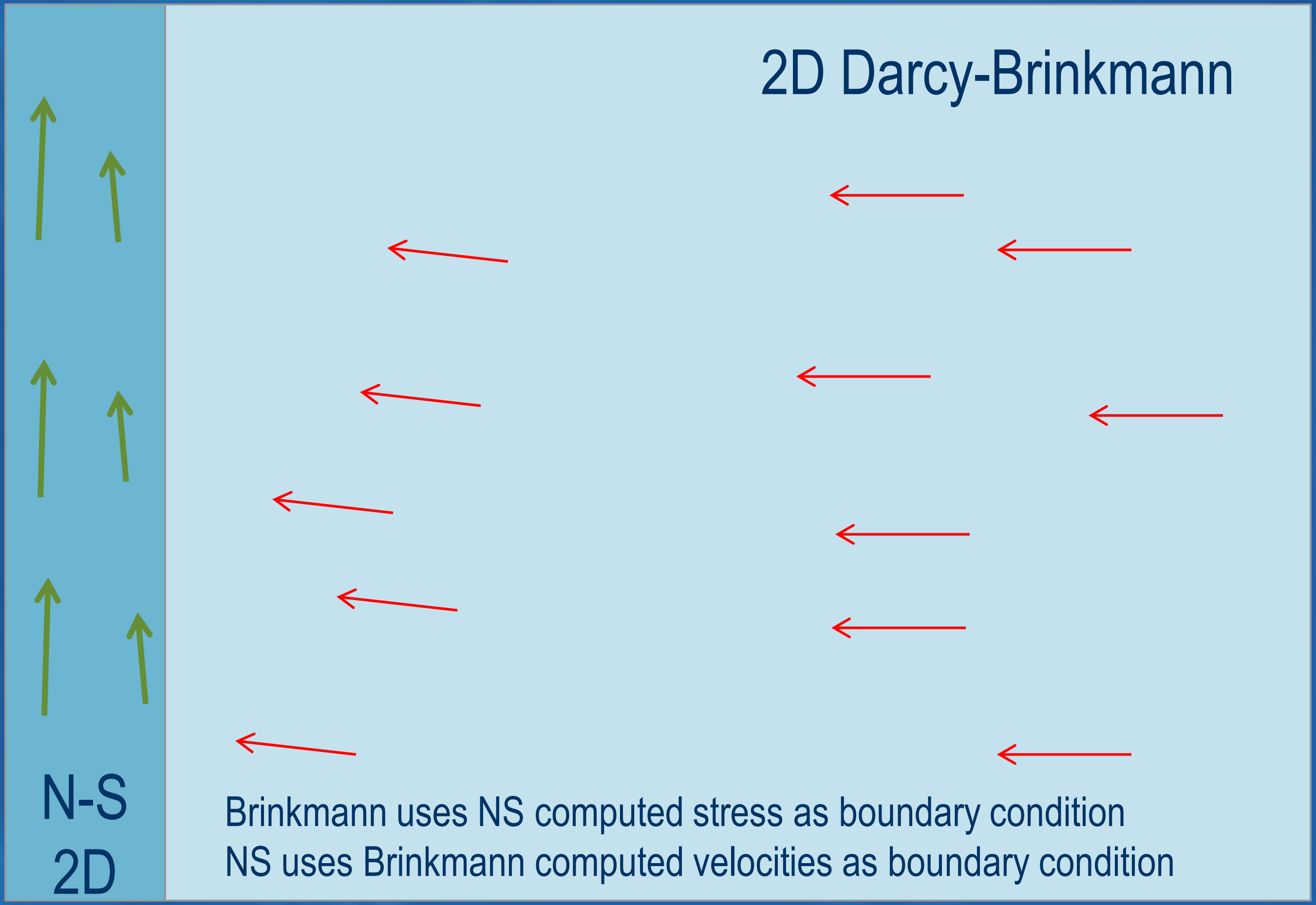
- Inside wellbore assume instantaneous change versus time (not transient formulation)
- 2D flow (both radial and axial flow)
- Model turbulence using standard CFD formulation, k-ε
- Boundary conditions need either radial and axial velocity, or radial and axial stress (i.e. two conditions, not one)

Go to equations – 2D Porous Media

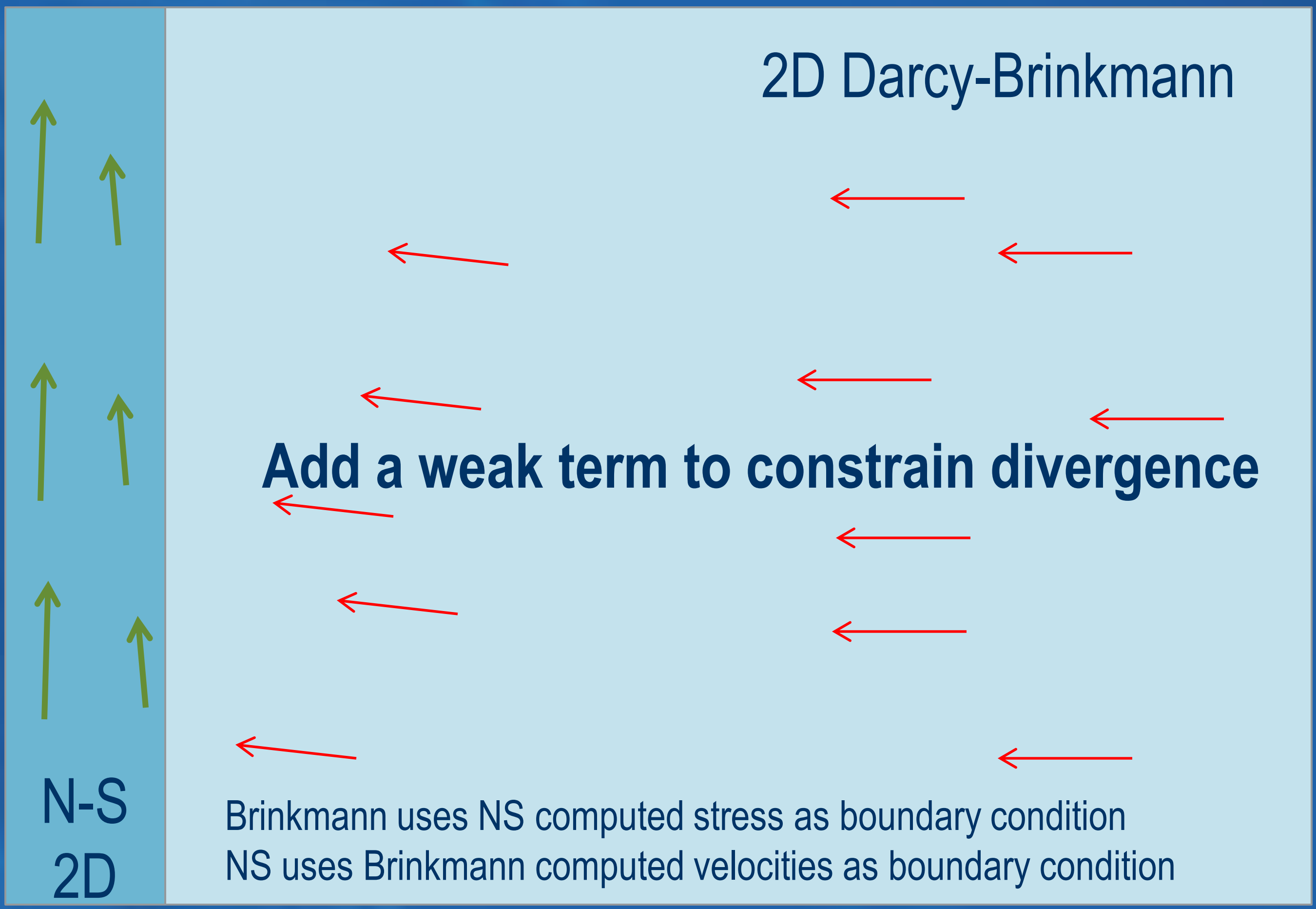
$$\frac{\rho}{\varepsilon_p}\frac{\partial u}{\partial t}+\left(\frac{\mu}{k}\right)u=\nabla p \qquad \frac{\partial}{\partial t}(\rho\varepsilon_p)+\nabla.(\rho u)=0$$

- Almost exactly same as Darcy's equation except the term $(\mu/k)u$. This term is only important near boundaries, but it changes the nature of the equation…
- Boundary conditions need either radial and axial velocity, or radial and axial stress (i.e. two conditions, not one)
- I.e., same as the Navier-Stokes, so we can match them up consistently

COMSOL Multiphysics



COMSOL Multiphysics – Stabilization



Go to equations – Heat Transfer

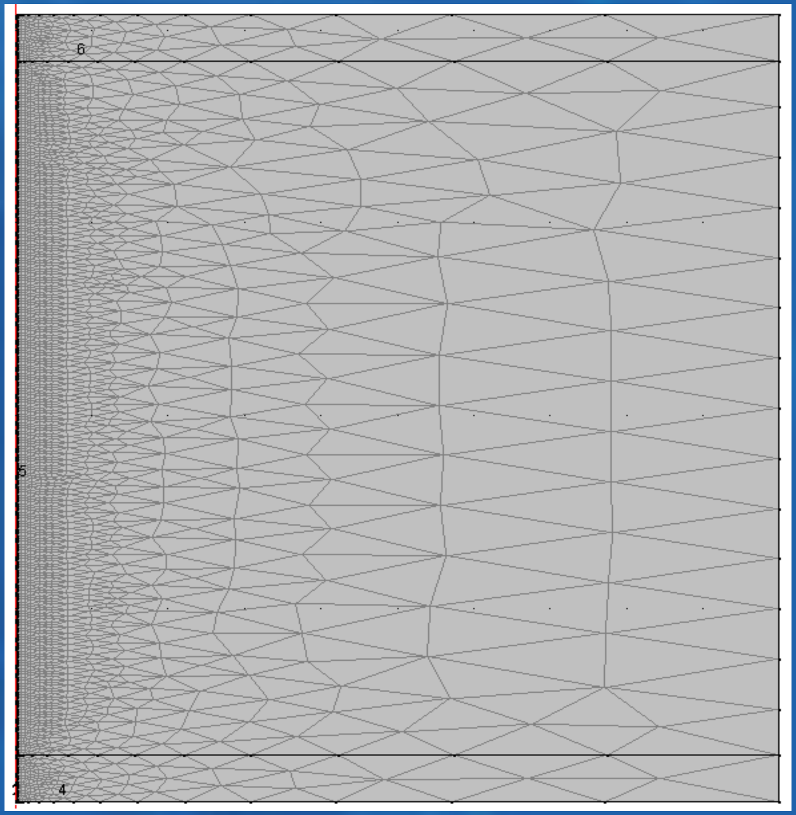
$$\rho_f C_{pf}\left(u\frac{\partial T}{\partial r}+w\frac{\partial T}{\partial z}\right)=\nabla.(\mathrm{k}\nabla\mathrm{T})+(\alpha T-1)\left(u\frac{\partial p}{\partial r}+w\frac{\partial p}{\partial z}\right)$$

- Term in red is Joule-Thomson effect…
- E.g., if pure radial flow (w=0) and conduction not important

$$\rho_f C_{pf}\left(u\frac{\partial T}{\partial r}\right)=(\alpha T-1)\left(u\frac{\partial p}{\partial r}\right)$$

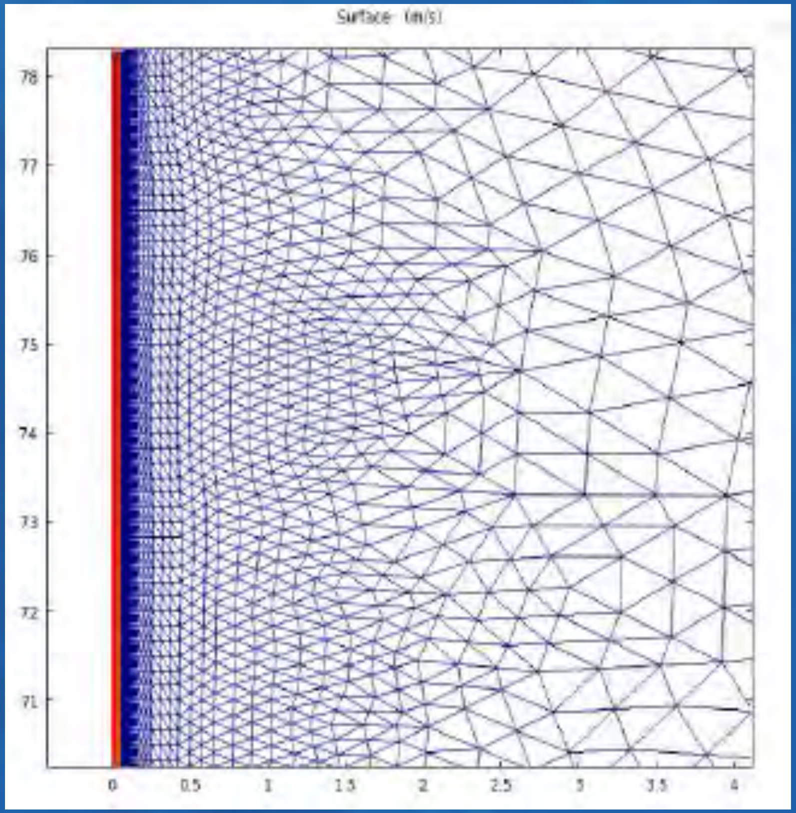
- i.e. $\Delta T = J\,\Delta P$ where $J = (\alpha T - 1)/(\rho C_p)$
- Note that J can be positive or negative (gas vs water vs oil)

Challenges



Mesh needs to be very fine in wellbore:
6” diameter, hundreds of meters long
Mesh fairly dense in annulus
Mesh coarse in the rock
Results in many elongated elements
Slows convergence

Challenges



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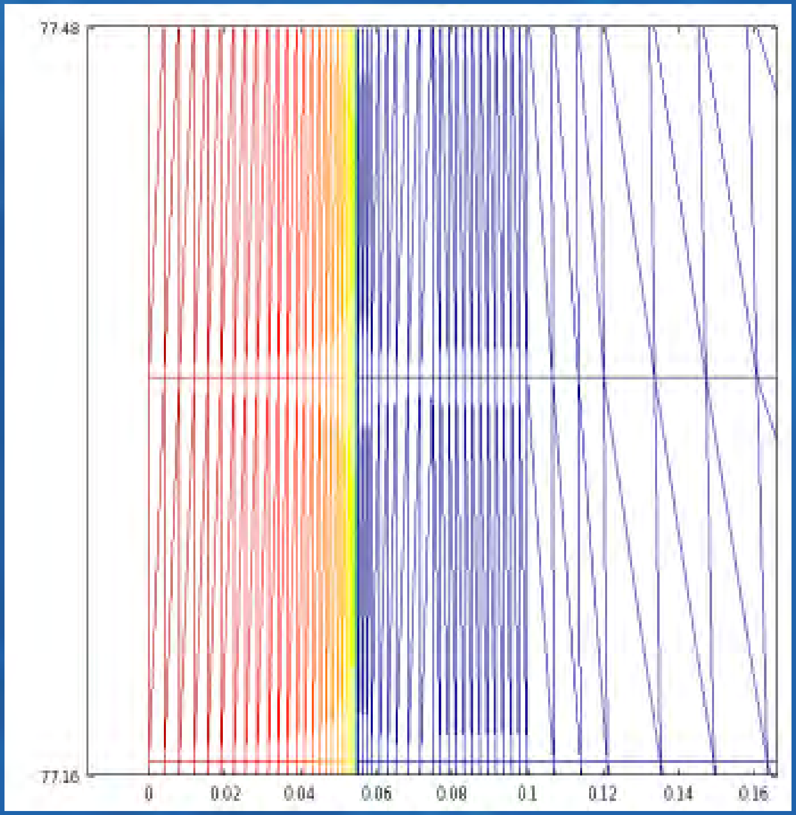

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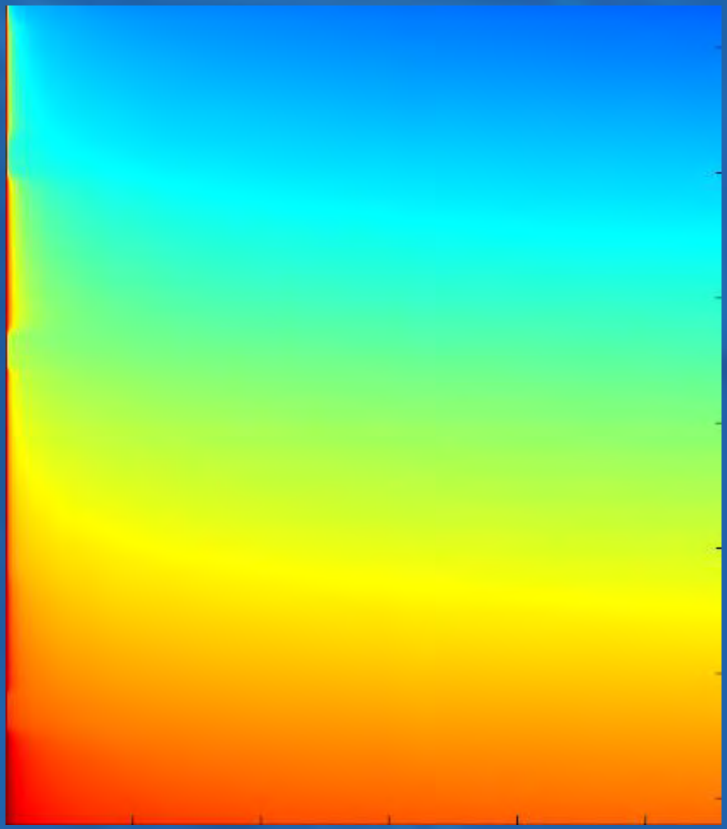


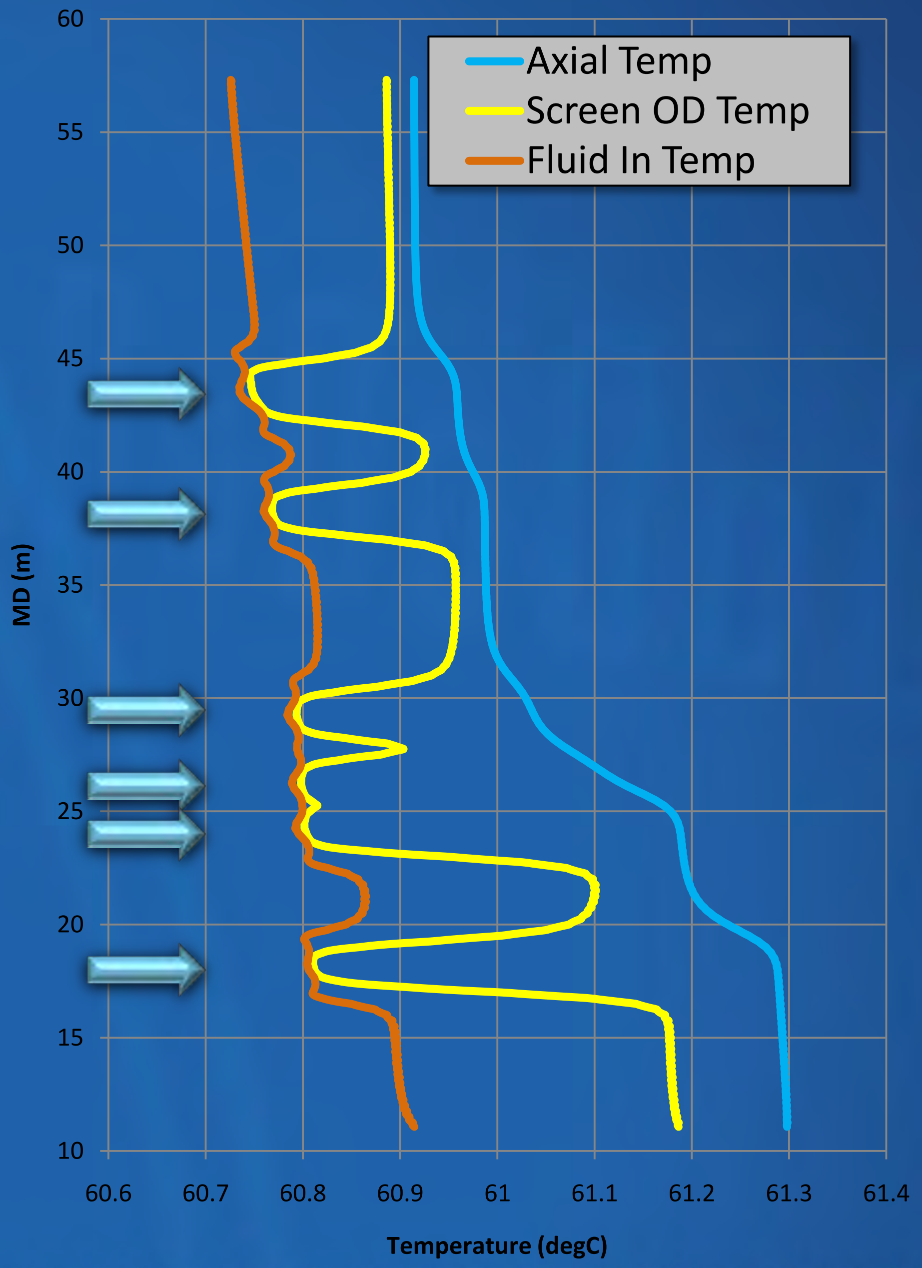
Mesh needs to be very fine in wellbore
Mesh fairly dense in annulus
Mesh Coarse in the rock
Results in many elongated elements
Slows convergence
~150,000 unknowns
Nonlinear equation for P
Weakly nonlinear in T
k-ε convergence often very painful
To get CFD to converge, started with uniform flow and used that as initial guess
~10 mins to solve one configuration

COMSOL Results

Example shown is 50m section with highly stratified flow. Hotter fluid is entering from below, gets cooled somewhat by fluid over this interval.

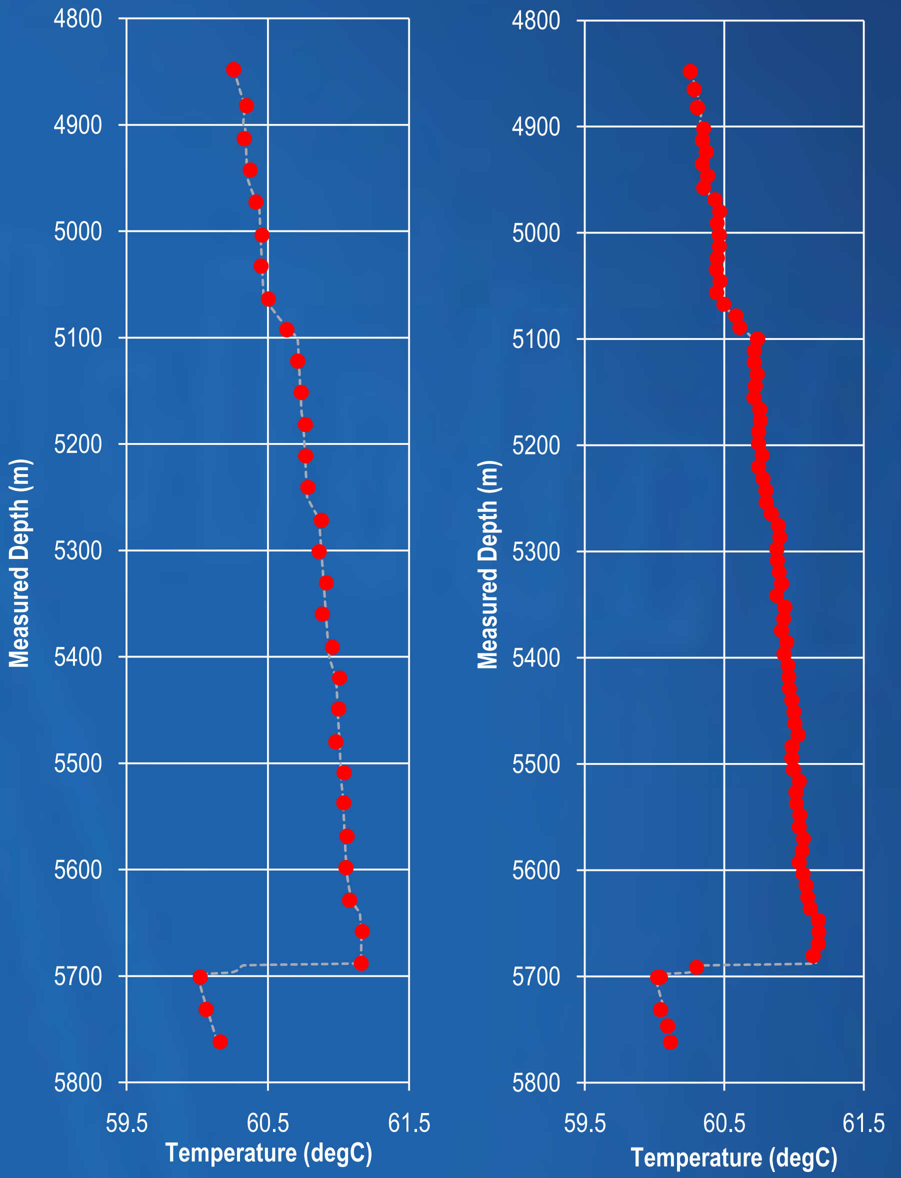
Zones dominated by radial flow measure the incoming fluid temperature.

Zones dominated by conduction measure close to the axial temperature.



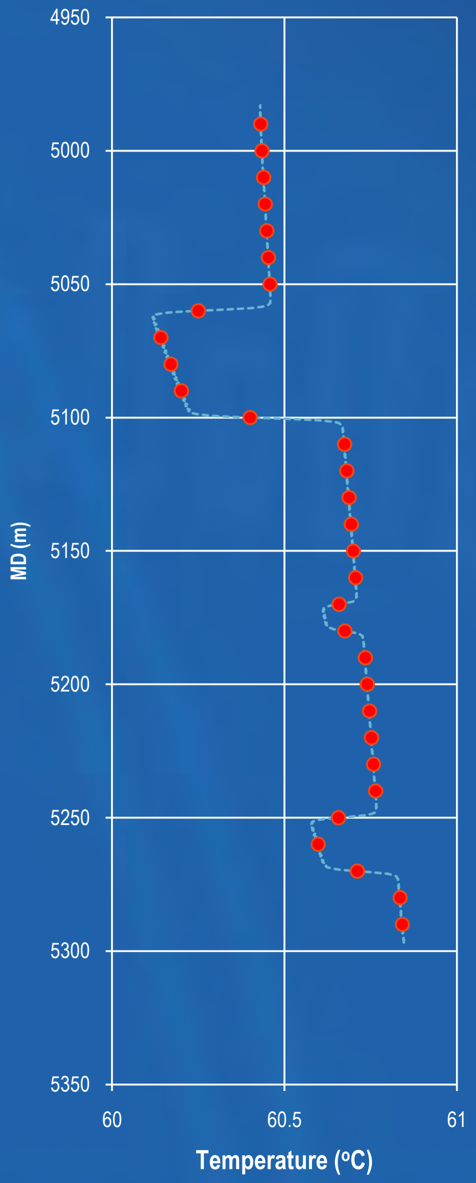
Some results – Large Sand Bodies

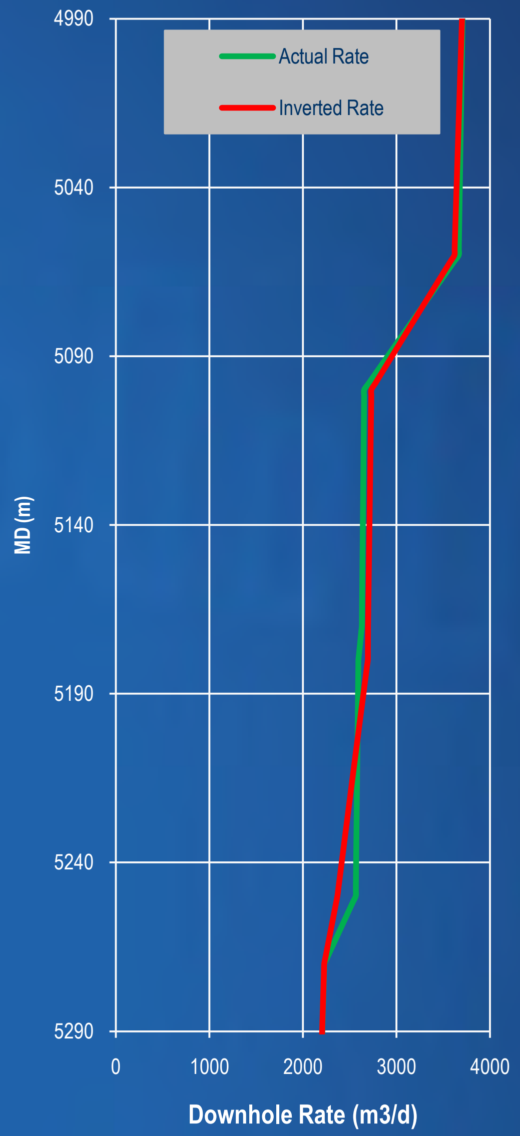
- 85 deg well, flow from large sand with varying permeability.
- 30m spacing and 10m spacing
- Coarse spacing captures overall temperature trend
- 10m preferable



Some results – Small Sand Bodies

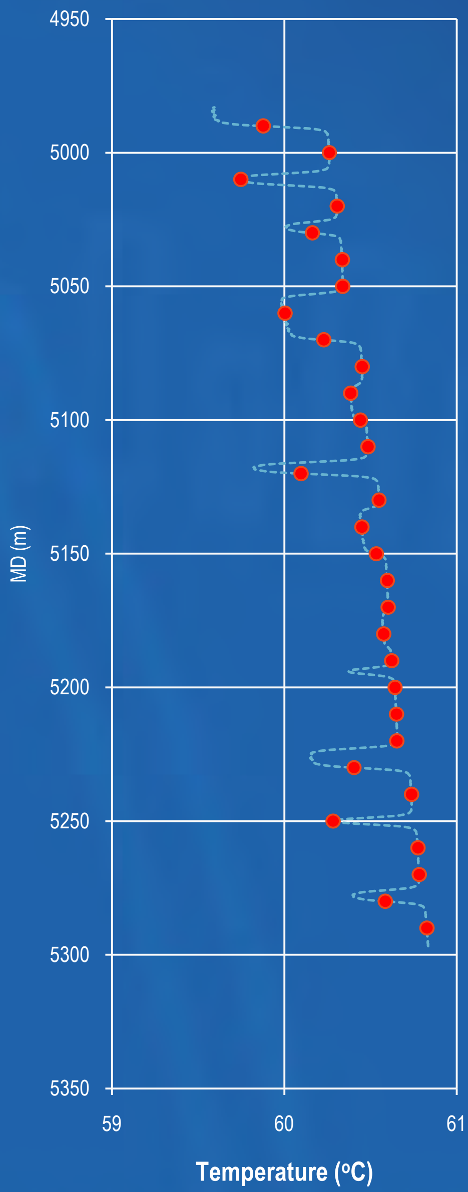
- 85 deg well, flow from sand blocks with different perms and separated by shales
- Open-hole gravel pack
- 10m sensor spacing
- Inverted flow rate based on the shale data only

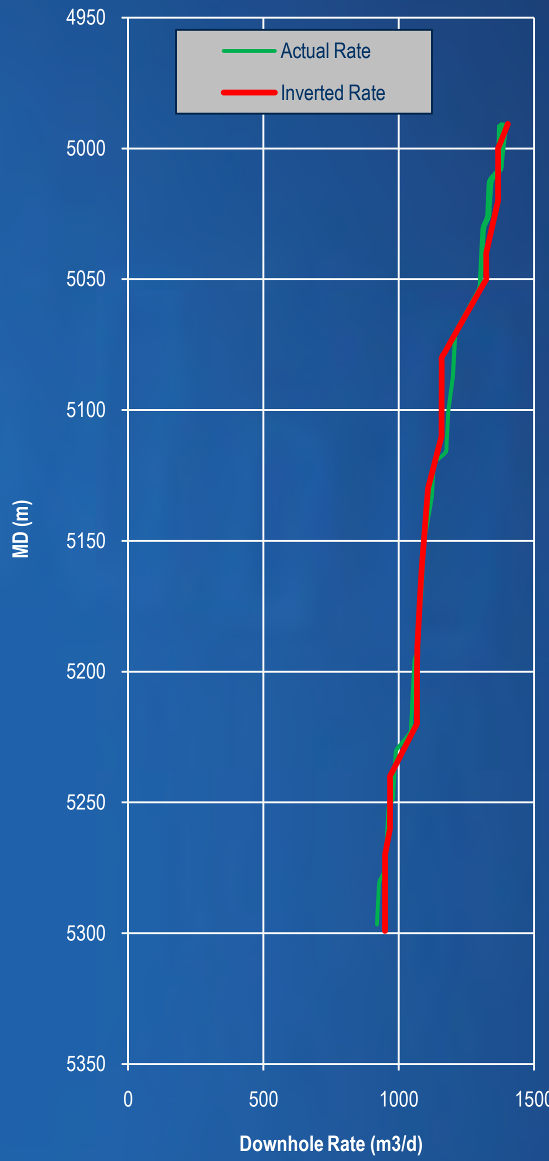




Some results – Flow from Vugs/Fractures

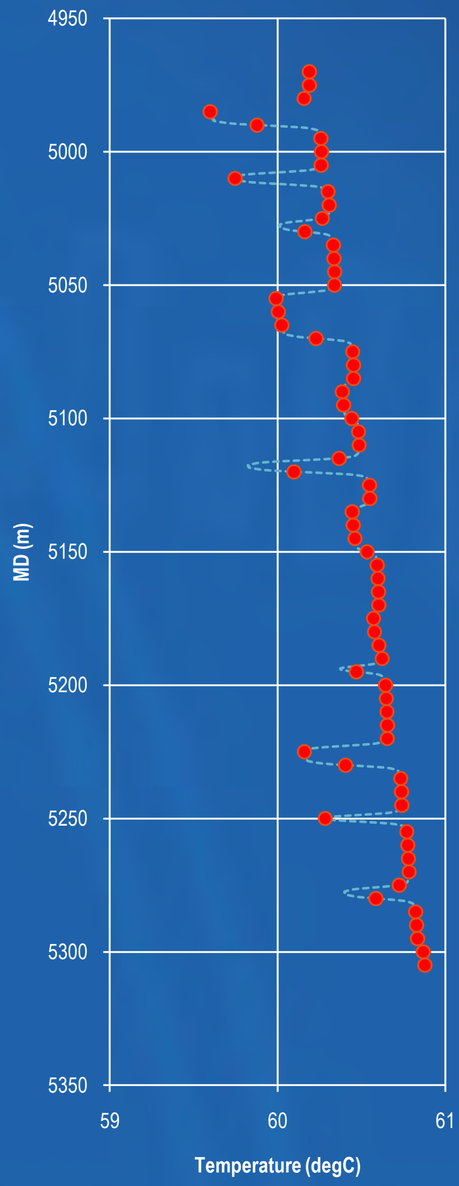
- 85 deg well, flow from very high perm vugs and fractures
- Open-hole gravel pack
- 10m sensor spacing
- Inverted flow rate vs actual

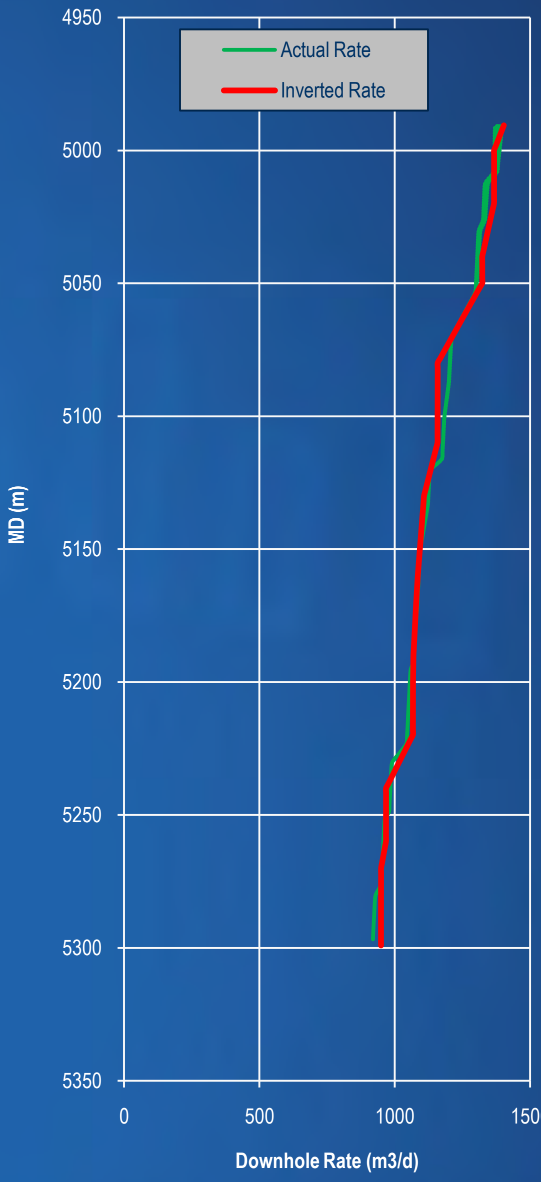




Some results – Flow from Vugs/Fractures

- 85 deg well, flow from very high perm vugs and fractures
- OHGP
- 5m sensor spacing
- Inverted flow rate vs actual

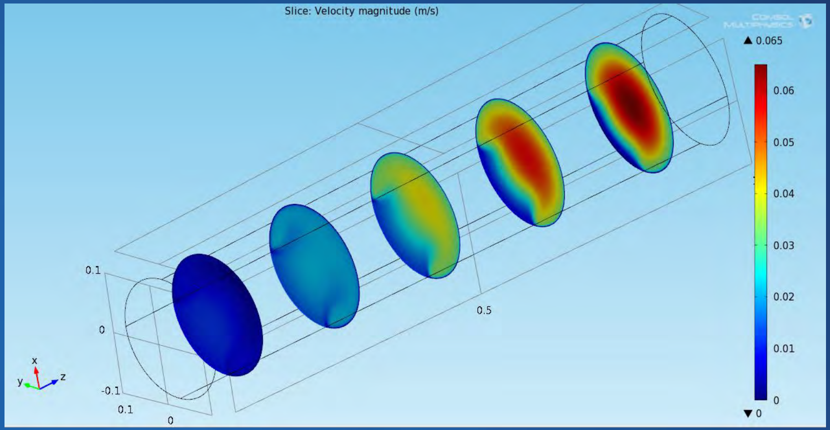




New Interface Condition at Wellbore

- Combination of k-ε and Brinkmann-Darcy gives a new interface condition for heat-transfer coefficient from reservoir to wellbore
- It lies in-between Sleicher-Rouse and Dittus-Boulter

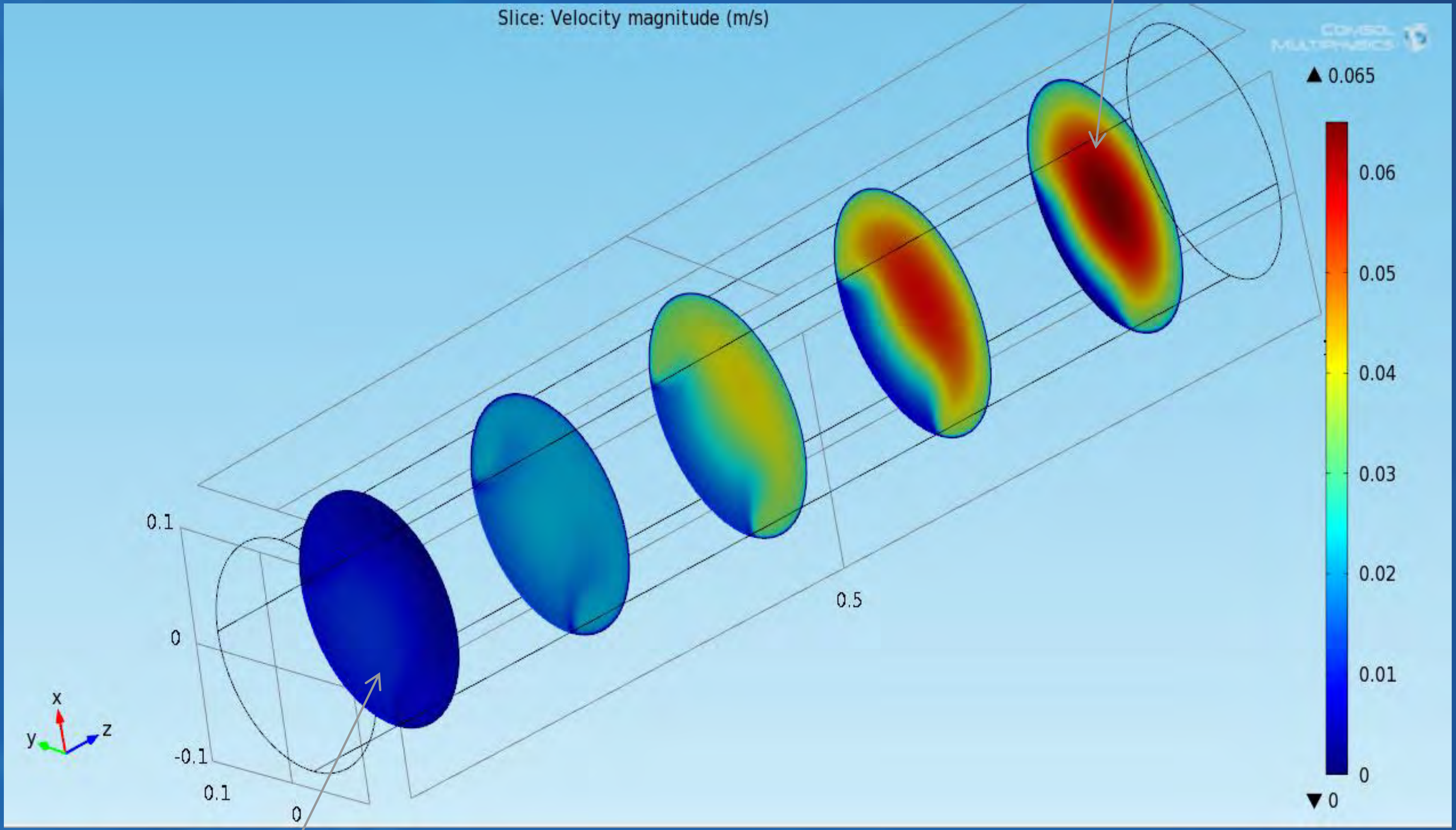
Future directions



- Improved physics at the interface:
  - Beavers/Joseph, etc
  - Effective viscosity of the Brinkmann equation vs fluid viscosity
- Integration of empirical PVT formula into the COMSOL set-up
- Stabilization of the k-ε (new empirical model for ε in a tube?)
- 3D – is the temperature on one side of the wellbore, the same as the other??

Future directions – 3D

Almost uniformly parabolic



Inject fluid from just one side of the wellbore

Conclusion

- Multiphysics FEM code can solve combination of porous media, wellbore CFD, advected temperature and temperature conduction
- Reproduces temperature phenomenon seen in sandface data
- Has been used in commercial applications to determine sensor spacing needed for accurate flow-profile inversion
- Has been used to validate when simplistic models can be used, and when they cannot
- Opportunities for new algorithms that take advantage of the difference between “real” temperature and simple models
- Understanding the near wellbore physics has proven crucial to accurate interpretation of temperature data